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Passive building energy savings: A review of building envelope components

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ABSTRACT

A significant portion of the total primary energy is consumed by today's buildings in developed countries. In many of these buildings, the energy consumption can be significantly reduced by adopting energy efficiency strategies. Due to environmental concerns and the high cost of energy in recent years there has been a renewed interest in building energy efficiency. This article strives to make an exhaustive technical review of the building envelope components and respective improvements from an energy efficiency perspective. Different types of energy efficient walls such as Trombe walls, ventilated walls, and glazed walls are discussed. Performance of different fenestration technologies including aerogel, vacuum glazing and frames are presented. Advances in energy efficient roofs including the contemporary green roofs, photovoltaic roofs, radiant-transmittive barrier and evaporative roof cooling systems are discussed. Various types of thermal insulation materials are enumerated along with selection criteria of these materials. The effects of thermal mass and phase change material on building cooling/heating loads and peak loads are discussed. Application of thermal mass as an energy saving method is more effective in places where the outside ambient air temperature differences between the days and nights are high. Air tightness and infiltration of building envelopes are discussed as they play a crucial role in the energy consumption of a building. Energy efficiency approaches sometimes might not require additional capital investment. For example, a holistic energy efficient building design approach can reduce the size of mechanical systems compensating the additional cost of energy efficiency features.

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Nomenclature

AAC	Autoclaved aerated concrete
ACH	Air changes per hour
APS	Arizona public service
ASHRAE	American society of heating, refrigerating and air-conditioning engineers
ASTM	American society for testing and materials
BIPV	Building integrated photovoltaics
BUR	Built-up roof
C	Dimensionless constant
CFCs	Chlorofluoro carbons
d	Gap thickness of the crack
DL	Daylighting
EC	Electrochromics
EPDM	Ethylene propylene diene monomer
EPS	Extruded polystyrene
ESP-r	Environmental systems performance-research
FRP	Fiber-reinforced plastic
HCFCs	Hydrochlorofluorocarbons
HOE	Holographic optical elements
HPI	High performance insulation
HTF	Heat transfer fluid
HVAC	Heating, ventilation and air conditioning
IECC	International energy conservation code
IR	Infrared
ISO	The International Standards Organization
L	Breadth of the crack
LASRS	Lightweight aluminum standing seam roofing systems
LEED	Leadership in energy and environmental design
LWC	Lightweight concrete
PCES	Phase change energy solutions
PCM	Phase change material
PIR	Polyisocyanurate
Q	Flow rate
RCC	Reinforced cement concrete
SC	Solar gain control
SCE	Solar collection envelope
SPD film	Suspended particle devices film
SR	Solar reflectance
TPO	Thermoplastic polyolefin
U	Thermal transmittance (in $W/m^2 K$)
UK	United Kingdom
US	United States of America
VR	Vaulted roof
WGBC	World green building council
z	Length in the direction of flow
ρ	Density
μ	Dynamic viscosity
Γ	Energy transmittance
α, β	Constants
ΔP	Pressure difference

1. Introduction

A significant portion of the energy is consumed by today's buildings in developed countries. For example, about 39% of the total US primary energy is consumed by buildings today [1], this fact emphasizes on the imperative need for energy savings in buildings. Both governments and scientific communities across the world have identified the potential and need for energy efficiency in the buildings, and initiated significant efforts in this direction. As of date, the WGBC (world green building council) has involved 82 nations all across the globe in taking up green building initiatives to some degree. LEED (Leadership in Energy and Environmental Design), an internationally recognized green building certification system, also identifies energy efficiency as an important attribute of green buildings.

Table 1
Code standard *U*-values (in W/m^2 K) for UK buildings.

Envelope element	1995 Standard *U*-values (W/m^2 K)	2000 Standard *U*-values (W/m^2 K)	Percentage reduction in *U*-value (%)
Walls	0.45	0.35	22
Roofs	0.25	0.16	36
Floors	0.45	0.25	44
Windows	3.3	2.2	33

Source: John et al. [6].

The buildings we find today are expected to achieve both energy efficient and environmental-friendly design. This idea of sustainable buildings encompasses various issues regarding energy, water, land and material conservation, together with environmental pollution and the quality of indoor and outdoor environments. A technical review on the recent developments in various building envelope components and their effects on the energy efficiency of a building is, therefore, highly relevant given the present context.

Building energy efficiency can be improved by implementing either active or passive energy efficient strategies. Improvements to heating, ventilation and air conditioning (HVAC) systems, electrical lighting, etc. can be categorized as active strategies, whereas, improvements to building envelope elements can be classified under passive strategies. Recent years have seen a renewed interest in environmental-friendly passive building energy efficiency strategies. They are being envisioned as a viable solution to the problems of energy crisis and environmental pollution.

A building envelope is what separates the indoor and outdoor environments of a building. It is the key factor that determines the quality and controls the indoor conditions irrespective of transient outdoor conditions. Various components such as walls, fenestration, roof, foundation, thermal insulation, thermal mass, external shading devices etc. make up this important part of any building. Several researchers around the world carried out studies on improvements in the building envelope and their impact on building energy usage. Energy savings of 31.4% and peak load savings of 36.8% from the base case were recorded for high-rise apartments in the hot and humid climate of Hong Kong by implementing passive energy efficient strategies. The strategies include adding extruded polystyrene (EPS) thermal insulation in walls, white washing external walls, reflective coated glass window glazings, 1.5 m overhangs and wing wall to all windows [2]. In a different study, the thermal and heat transfer performance of a building envelope in subtropical climatic conditions of Hong Kong was studied using the DOE-2 building energy simulation tool. An energy effective building envelope design saved as much as 35% and 47% of total and peak cooling demands respectively [3]. In Greece, thermal insulation (in walls, roof and floor) and low infiltration strategies reduced energy consumption by 20–40% and 20% respectively. According to the same study, external shadings (e.g. awnings) and light-colored roof and external walls reduced the space cooling load by 30% and 2–4%, respectively [4]. Several numerical studies were also carried out on building envelopes and individual building envelope components. A detailed model of transient heat transfer through a typical building envelope developed by Price et al. [5] takes into account the convection and thermal radiation heat exchange at the interior and exterior surfaces of the building.

Over the years, code requirements on building envelopes have improved significantly, and continue to increase in performance. Table 1 shows how building envelope standards in the UK have changed over time. With each revision, the building envelope standards were upgraded substantially, emphasizing the growing need for energy conservation. In the United States, although different states implement different code standards, they are all derivatives from various versions of American society of heating refrigeration and air-conditioning engineers (ASHRAE) and International Energy Conservation Code (IECC) standards. The latest version of ASHRAE standard is ASHRAE 90.1-2007 and the IECC standard is IECC 2009.

Advanced and sustainable materials research for building envelope applications has seen significant progress in recent years. Fiber-reinforced plastic (FRP) is one such advanced composite material that can be used in wall and roof applications [7]. Sustainable earth material such as unfired clay bricks, a straw–clay mixture and straw bales were investigated for use in new or upgrading historical earth wall constructions [8]. These earth wall constructions can comply with the UK building regulations for thermal transmittance of less than 0.35 W/m^2 K.

A proper architectural design of a building envelope can significantly lower the energy usage through daylighting, reduced HVAC loads, etc. Innovations such as the self-shading envelopes are being explored by researchers. A nomogram simulation of a solar collection envelope (SCE) was discussed by using a computer modeling tool called SustArc [9]. The SCE concept is used to generate self-shading envelopes. In efficient self-shading envelope designs, the summer sun is blocked while the winter sun is permitted.

The most important building envelope components and their latest developments are discussed in the following sections.

2. Walls

Walls are a predominant fraction of a building envelope and are expected to provide thermal and acoustic comfort within a building, without compromising the aesthetics of the building. The thermal resistance (*R*-value) of the wall is crucial as it influences the building energy consumption heavily, especially, in high rise buildings where the ratio between wall and total envelope area is high. The market available center-of-cavity *R*-values and clear wall *R*-values consider the effect of thermal insulation. However, the influence of framing factor and interface connections is not taken into consideration [10].

Walls with thermal insulation have a higher chance of surface condensation when the relative humidity of ambient air is greater than 80%, provided the convective and radiative heat transfer coefficients of the exterior wall are small. This problem is more severe during winter months and in colder climatic regions with higher humidity levels [11]. This moisture condensation on building exterior walls promotes undesirable microbial growth which might reduce the wall life and lead to other undesirable conditions in the building. Conventionally, based on the materials used in construction, walls can be classified as wood-based walls, metal-based walls and masonry-based walls. There are other types of advanced building wall designs that are applied to improve the energy efficiency and comfort levels in buildings. The following sections describe such advanced wall technologies.

2.1. Passive solar walls

Typically used in cold climates, the walls that trap and transmit the solar energy efficiently into the building are called passive solar walls. This type of walls were first developed by E.S. Morse in the 19th century and later redesigned by Trombe et al. In these walls, typically, a 12-inch-thick concrete wall is used as a south (for geographical northern hemisphere) façade to absorb solar radiation. A glazing is used as an outer covering of the wall to provide the greenhouse effect. Several developments resulted from the basic designs of classical Trombe wall and composite Trombe–Michell wall [12–17]. One such Trombe wall system design proposed for cold climatic conditions has a steel panel backed with polystyrene

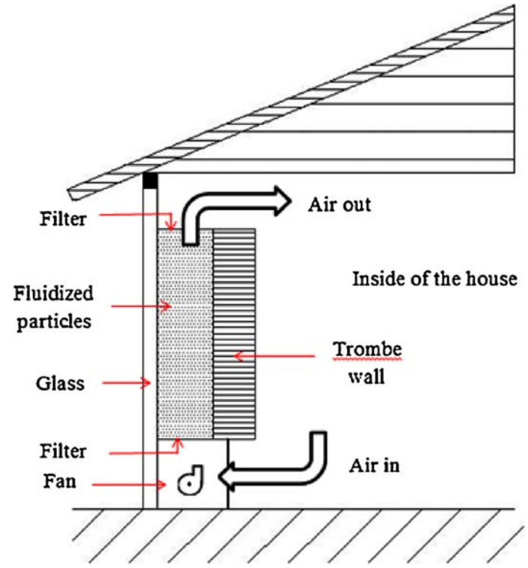


Fig. 1. A cross-sectional view of fluidized Trombe wall system with part details.
Source: Tunç and Uysal [19].

insulation mounted on the south façade. This design improved the operating efficiency of the classical Trombe wall by 56% [15]. A comparative study was conducted on four different kinds of solar wall configurations—unventilated solar wall, Trombe wall, insulated Trombe wall and composite solar wall—using numerical simulations. All of these walls, except the unventilated solar wall, transfer heat to the indoors both by conduction through wall and convection through circulating air. The unventilated solar wall transfers heat exclusively through conduction. A more convection-based type (controllable) of solar wall such as composite solar wall or insulated Trombe wall is preferable in regions with shorter heating seasons in order to avoid overheating in cooling season. Whereas a more conduction-based type (uncontrollable) of solar wall such as Trombe wall or unventilated solar wall is preferable in regions with longer heating seasons. However, the problem of overheating in summer can be prevented through the use of solar shields [14]. Jie et al. [17] have proposed an innovative design of PV integrated Trombe wall. In this design, PV cells are affixed on the back of the transparent glass cover of a normal Trombe wall. Both the heat rejected by the PV cells and the heat absorbed by the thermal mass of Trombe wall are used for space heating. A theoretical analysis on a Trombe wall with fin-type structured outer wall surface design suppresses the convective and infrared (IR) radiation heat losses from the wall's outer face to the glass cover thereby encouraging the conduction through the wall along with convective and radiative heat exchange to the inside of the room [16]. Phase change material (PCM) based Trombe walls have been reviewed [18]. Experimental results suggest that PCM Trombe walls were thinner and also performed better than concrete walls. A novel concept of fluidized Trombe wall system (as shown in Fig. 1) where the gap between the Trombe wall and the glass cover is fluidized with highly absorbing, low-density particles is introduced [19]. The solar energy absorbed by these highly absorptive particles is transferred to the indoors through fan-circulated air. A filter at the top of the air channel checks the fluidized particles from entering the indoor space. The overall efficiency of this design is higher compared to a classical Trombe wall design as the air (heat transfer fluid (HTF)) is in direct contact with the fluidized particles.

A Transwall (as shown in Fig. 2) is a transparent modular wall that provides both heating and illumination of the dwelling space.

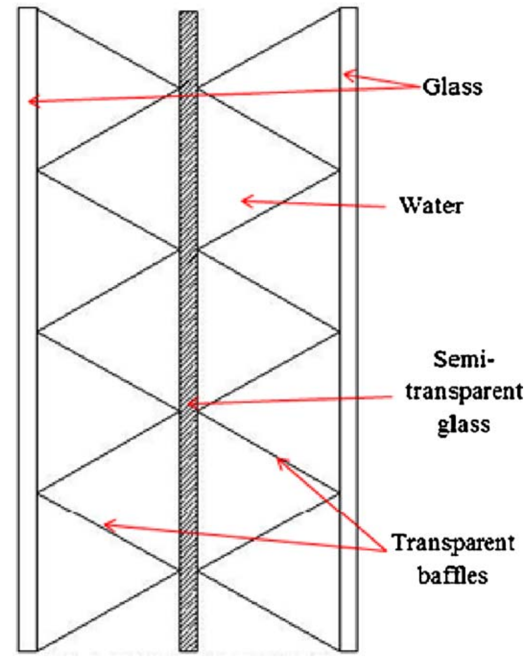


Fig. 2. A cross-sectional view of Transwall system with part details.
Source: Nayak [20].

These walls are comprised of water enclosed between two parallel glass panes supported in a metal frame. A semi-transparent glass absorbing plate is at the center of the parallel glass panes. The incident solar radiation is partially absorbed by the water and semi-transparent glass plate, the rest of the transmitted radiation causes both heating and illumination that are required by the indoors [20].

2.2. Lightweight concrete (LWC) walls

Lightweight concrete (LWC) refers to any concrete produced with a density of less than 2000 kg/m^3. For structural purposes, the LWC density often ranges between 1600 and 2000 kg/m^3 along with a strength grade of 15 MPa. Whereas for thermal insulation purposes the density is often less than 1450 kg/m^3 along with strength grade as low as 0.5 MPa. The thermal resistance of light weight concrete can be improved by mixing with light weight aggregates. These aggregates can come from natural material (such as pumice, diatomite, expanded clay or expanded shale, etc.), processed by-products (such as foamed slag, sintered pulverized fuel ash) or unprocessed materials. The low-conductivity aggregates such as polystyrene beads, vermiculite and leca have been focus of research in recent years [21]. Autoclaved aerated concrete (AAC) is a type of LWC produced by introducing aluminum powder to generate miniscule air bubbles. It has superior thermal resistance than other types of LWC. AAC is first introduced in the early 20th century in Europe, and it is gaining popularity as exterior and interior wall material as an alternative to clay bricks in recent years in developing countries. The density of AAC ranges between 600 and 800 kg/m^3. All kinds of LWC walls are particularly useful in countries where concrete construction is predominant and the use of insulation in walls is not a common practice. Also, they can be constructed faster using less skilled labor.

2.3. Ventilated or double skin walls

An air gap between two layers of masonry wall braced with metal ties constitutes a ventilated or double skin wall. They are also called cavity walls. There are two basic kinds of ventilated walls, one

with forced ventilation in the cavity, and the other with natural ventilation (stack effect). Most commonly, ventilated walls are used to enhance the passive cooling of buildings. Ciampi et al. [22] developed a mathematical model to evaluate the energy performance of a ventilated wall. They validated this model for 6 different ventilated wall designs. Although, energy savings for all the wall designs increase with the increase in width of the air gap, however, further increase over 0.15 m yielded only diminishing returns. A typical summer cooling energy savings of 40% can be achieved with a carefully designed ventilated wall. However, poor construction quality can introduce thermal bridge issues. Also, the parameters such as the thermal resistance of the exterior wall and relative roughness of the slabs delimiting the air duct are important.

2.4. Walls with latent heat storage

The phase change material (PCM) is incorporated in light weight wall structures to enhance the thermal storage capacity. PCM material is impregnated commonly in gypsum or concrete walls. Porous material such as plasterboard has better PCM impregnation potential than pumice concrete blocks. The thermal heat storage in PCM based walls depends on the amount (weight %) of PCM material impregnated in the wall material. The microencapsulation of PCM material in wall construction material has allowed this PCM weight ratio to about 30% in gypsum. Recent years have seen the advent of composite materials that can encapsulate PCM up to 60% by weight. Athienitis et al. [23] compared PCM based and non-PCM based gypsum board for inside wall lining and concluded that the PCM based wall lining lowered the maximum room temperature by 4 °C and reduces the heating demand during night. In a separate study, experimental results on PCM based composite wall boards showed a decrease in maximum room temperature by 4.2 °C [24].

3. Fenestration (windows and doors)

Fenestration refers to openings in a building envelope that are primarily windows and doors. The fenestration plays a vital role in providing thermal comfort and optimum illumination levels in a building. They are also important from an architectural standpoint in adding aesthetics to the building design. In recent years, there have been significant advances in glazing technologies. These technologies include solar control glasses, insulating glass units, low emissivity (low-e) coatings, evacuated glazings, aerogels and gas cavity fills along with improvements in frame and spacer designs [25]. A simulation study was carried out on 10 different glazing types applied to five different climatic zones in India [26]. It was observed that the annual energy savings by a window is dependent on not just the thermal conductivity (*U*-value) and the solar heat gain coefficient (SHGC or *g*-value) of the window but also on its orientation, climatic conditions and building parameters such as insulation level, floor area, etc.

For passive solar heating applications, windows with low U-value and high total solar energy transmittance (Γ) are preferred. A tradeoff should be made between *U*-value and solar transmission as most likely the measures to lower *U*-value shall lower the solar transmission [25]. In daylighting applications, spectrally selective low-e coatings allow the visible light of the solar spectrum and block the other wavelengths that are generally responsible for solar heat gains. These coatings are placed on the inside surface of the outermost pane, as most absorbed solar energy will be dissipated to the ambient air [25]. Low-e coatings are of two types: hard coating and soft coating. The hard coating is a tin oxide based coating whereas the soft coating is usually a thin layer of silver surrounded by dielectric protective layers. Typically, soft silver-based coatings have a lower solar transmittance and higher infrared reflectance compared to hard tin oxide-based coatings [27]. The visible transmittance of a low-e tin oxide-based glazing is increased by antireflection treatment with silicon dioxide (SiO_2). The measured percentage increase of integrated visible transmittance was 9.8% and a transmittance value of 0.915 was achieved [27]. This permits the usage of antireflection treated low-e glazing in the construction of triple glazing unit windows which has desirable *U*-value while not decreasing the visibility.

3.1. Types of glazing materials and technologies

State-of-the-art glazing materials and technologies that are aimed at providing high performance insulation (HPI) or solar gain control (SC) or daylighting (DL) solutions or a combination are presented in this section.

3.1.1. Aerogel glazing

Aerogels are a category of open celled mesoporous solids with a volume porosity of greater than 50%. They have a density in the range of 1–150 kg/m^3, and are typically 90–99.8% air by volume. They can be formed from a variety of materials, including silica, alumina, lanthanide and transition metal oxides, metal chalcogenides, organic and inorganic polymers and carbon. Aerogel glazing entered the contemporary glazing market in the year 2006 and is, essentially, a granular aerogel encapsulated between polycarbonate construction panels that weigh less than 20% of the equivalent glass unit and have 200 times more impact strength. Light transmission and *U*-value of aerogel panels are a function of panel thickness. Their high performance, low density and outstanding light diffusing properties make them an appropriate choice for roof-light applications [28].

3.1.2. Vacuum glazing

Vacuum space is created between two glass panes to eliminate the conductive and convective heat transfers between the glass panes reducing the center-of-glass *U*-value to as low as 1 W/m^2 K. Most often, low-e coating is applied on one or both of the glass panes to reduce the re-radiation into the indoor space [29]. Although, the technology faces some challenges in maintaining vacuum for longer periods, it is still a widely used energy efficient glazing option [28]. An exhaustive study is presented on the processes and the costs involved in the fabrication of vacuum glazing [30]. Also a comparison between the vacuum and argon filled double glazing is discussed. Heat transfer through evacuated triple glazing, a prospective glazing technology, was investigated by using analytical thermal network modeling and numerical finite element modeling [31]. The findings suggested that a triple vacuum glazing with a center-of-glazing thermal transmittance of less than 0.2 W/m^2 K is achievable.

3.1.3. Switchable reflective glazing

Switchable reflective glazing is essentially a variable tint glazing and is typically suitable for cooling load dominant buildings with large solar gain [29]. In some types of switchable reflective glazing, the optical properties change as a function of the incident solar radiation, either by applying a low DC voltage (electrochromics (EC)) or by using hydrogen (gasochromics) to change from bleached to colored state. In others, light guiding elements such as switchable reflective light shelves reflect solar radiation [28]. A life cycle energy analysis performed on EC windows, operating in Greece, have shown an energy reduction of 54% which corresponding to 6388 MJ, compared to a standard window during a life of 25 years [32]. The payback period was found to be about 9 years and the total energy cost savings ranged from 228 to 569 €/m^2 for 10 and 25 years of EC window operation respectively. Currently, there are

cost, warranty, switching time, glare and color rendering issues thwarting the marketability of this glazing technology.

3.1.4. Suspended particle devices (SPD) film

An SPD film is laminated between two glass panes. The SPD film has light absorbing particles that are randomly aligned in their normal state forming an opaque barrier. When voltage is applied, the particles align perpendicular to the plane of the glazing creating a transparent glass. The switching time (~1 s) is faster than EC glazing. This technology suffers from drawbacks such as radiant temperature, glare, color rendering, clearness and lifetime [28].

3.1.5. Holographic optical elements

Holographic optical elements (HOE) are light guiding elements comprising a holographic film sandwiched between two glass panes. The incident solar radiation is redirected, at a predefined angle through diffraction at the holographic film layer, usually onto the ceiling of the building interior. This can be used as a possible daylighting application. It suffers from some setbacks such as glare effects, light dispersion, milky clearness, limited exposure range of azimuth and zenith angles, etc. This technology is not yet commercialized [28].

3.2. Frames

The edge components (frame and spacer) of advanced fenestrations should minimize thermal bridging and infiltration losses. The effect of various combinations of frames and spacers on the *U*-value of different types of windows is described by Robinson and Hutchins [25]. Also, these edge effects are more pronounced in case of smaller size windows. The emphasis of low conductance frames was reiterated by Gustavsen et al. [33] in their review on low conductance window frames.

4. Roofs

Roofs are a critical part of the building envelopes that are highly susceptible to solar radiation and other environmental changes, thereby, influencing the indoor comfort conditions for the occupants. Roofs account for large amounts of heat gain/loss, especially, in buildings with large roof area such as sports complexes, auditoriums, exhibition halls etc. In accordance with the UK building regulations, the upper limits of *U*-value for flat roofs in 1965, 1976 and 1985 were 1.42 W/m^2 K, 0.6 W/m^2 K and 0.35 W/m^2 K, respectively. Currently, 0.25 W/m^2 K or less is required for all new buildings in the UK [34]. This reduction in the *U*-value over the years emphasizes the significance of thermal performance of roofs in the effort to increase the overall thermal performance of buildings.

Some passive cooling techniques could be implemented in tropical climates as result of modification in roof architecture. These include a compact cellular roof layout with minimum solar exposure, domed and vaulted roofs, naturally or mechanically ventilated roofs, micro ventilated roofs, high roofs and double roofs. Other methods such as white-washed external roof surfaces to reduce solar absorptivity, roofs covered with vegetation to provide humidity and shade, and usage of high thermal capacity materials such as concrete to minimize peak load demand are also gaining popularity. Roof shading is one way of reducing the impact of solar radiation on the roof surface. Economical roof shading is usually achieved with local material such as terracotta tiles, hay, date palm branches, inverted earthen pots, etc. which can usually contribute to a 6 °C drop in the indoor temperature [35]. Roof coatings are another way to mitigate the impact of solar radiation on the roof surface. High solar reflectance and high emissivity are the respective daytime and nighttime factors that govern the selection of a roof coating. Aluminum-pigmented coatings are less desirable because of their low infrared emittance. A cool coating can reduce a white concrete roof's surface temperature by 4 °C during a hot summer day and by 2 °C during night [35]. Most often, compound roofing systems are used to bring about the desired roof characteristics depending on the climatic conditions of the building location. A wide variety of roofing systems has emerged, and several of these are discussed in the following section.

4.1. Types of roofs

Roofs can be classified into different categories based on the type of construction. The following sections present some of the commonly used roofing structures along with recent developments.

4.1.1. Masonry roofs

In the developing countries of South Asia and the Middle East, masonry houses with reinforced cement concrete (RCC) roofs are popular owing to their pest (termite) resistance, natural calamity (cyclones) resistance, availability and cost effectiveness of concrete ingredients [36]. During tropical summers, they tend to exhibit unfavorable thermal characteristics such as higher soffit temperature and longer heat retaining capacity that affect the indoor air comfort conditions and increase energy costs. The indoor temperatures exceed 40 °C due to high roof temperatures of about 65 °C [35]. Higher soffit temperatures make them emit long wavelength infrared radiation towards the occupants. Even worse is that it might continue into the night due to the heat capacity of the slab. Also, the absorbed heat may lead to cracks in the supporting structure mainly made up of brick work or block work. This problem of high roof temperatures can be mitigated by employing roof shading, cool roof coatings or compound roof systems. A compound roof system developed with a combination of radiation reflectors and thermal insulation demonstrated substantial lowering of the heat conducted through a concrete roof [37]. An insulated concrete roof system with an antisolar coating proved successful in the tropical climatic conditions of Pakistan [38]. By lowering the roof temperature using this system, it was observed that the roof heat gain in summer was reduced by 45 kWh/day for a roof area of 208 m^2. Also, the overall heat transfer coefficient of the roof is reduced from 3.3 W/m^2 K to 0.54 W/m^2 K.

4.1.2. Lightweight roofs

Lightweight aluminum standing seam roofing systems (LASRS) are popularly used on commercial and government buildings as they are economical. However, they are wind sensitive due to weak seam-clip connection and also have bad thermal characteristics. Two easy ways to improve thermal characteristics of these roofs are by adding thermal insulation and using light colored roof paint. It was determined that the lighter colored surfaces such as white, off-white, brown and green yielded 9.3%, 8.8%, 2.5% and 1.3% reduction in cooling loads compared to an black-painted LASRS surface [39]. Recent investigations have revealed that the LASRS with glass fiber insulation does not suit well for hot and humid climates due to the interstitial condensation in the glass fiber layer. Alternative thermal insulation materials such as polyurethane, polystyrene or a combination of these have been evaluated [39]. These roofing systems, modeled and tested on an indoor stadium with a large roof surface area of 51 m × 41 m, indicated that roof structure with polyurethane insulation and white painted top surface performed better and saved 53.8% of the peak cooling load compared to a dark painted roof with glass wool insulation [39]. This can be attributed to the low thermal conductivity and thermal diffusivity of the polyurethane material and higher reflectivity of light colored roof surface.

4.1.3. Ventilated and micro-ventilated roofs

The ventilated roof systems are essentially two slabs delimiting a duct through which air flows. This air gap/air flow diminishes the heat transfer across the roof into the building. Ventilated roofs can be either a passive type, with stack effect driving the air flow, or an active type, with fan induced ventilation. They are more popular in hot climatic conditions and are particularly useful in moderate height and wide roof area buildings. Depending on the size of the duct, the flow through it is either laminar or turbulent. A detailed energy analysis conducted on ventilated roof buildings confirmed that an energy savings of 30%, during Italian summer, can be achieved when compared to non-ventilated roof buildings [40]. During cold winters, it is advisable to close the air duct using suitable dampers from an energy savings standpoint. These dampers favor only a very small ventilation to drain off any possible condensate in the duct.

4.1.4. Vaulted and domed roofs

Vaulted and domed roofs are quite popular in the vernacular architecture of the Middle East where the climatic conditions are hot and arid. Tang et al. [41] performed detailed finite element modeling of both vaulted roof (VR) and flat roof to compare their thermal performance in various climatic conditions. The half rim angle of a VR should be greater than 50° for it to show favorable influence on the indoor thermal conditions. South–north orientation of VR is more advantageous than east–west orientation. Also, they are only suitable for hot and dry climates, due to the presence of larger beam component of the solar radiation which is effectively reflected by the curved roof surface, and not so much for hot and humid climates [41]. Although VRs absorb more heat during the daytime than flat roofs, they also dissipate more heat through natural convection and re-radiation. Also, during night times, typical desert climate experiences colder ambient temperatures causing the VRs to dissipate heat even faster. High thermal stratification occurs inside VR buildings, with almost 75% of the stratification taking place in the volume under the vault, keeping the lower part of the building space cool. The hot air can be exhausted near the top of the gable walls of vaults [41].

4.1.5. Solar-reflective/cool roofs

Solar-reflective roofs or cool roofs are high solar reflectance and high infrared emittance roofs. They maintain lower roof surface temperature and inhibit the heat conduction into the building. Two surface properties that affect the thermal performance of these roof surfaces are solar reflectance (SR) (reflectivity or albedo) and infrared emittance (or emissivity). Conventional roofing materials have a SR of 0.05–0.25. Reflective roof coatings can increase the SR to more than 0.60. Most roofing materials have an infrared emittance of 0.85 or higher, with the exception of metals, which have a low infrared emittance of about 0.25. Therefore, even though metals are very reflective (i.e. SR greater than 0.60), bare metal roofs and metallic roof coatings tend to get hot since they cannot emit the absorbed heat effectively as radiation. Special roof coatings can raise the infrared emittance of bare metal roofs [42]. As shown in some cases in Table 2, by increasing SR or infrared emittance, the roof surface temperature can be lowered. A white elastomeric coating or aluminum coating can raise the SR value more than 0.50. Additionally, the SR increases with coating thickness for some products [42]. To find the influence of highly reflective roofs on cooling and peak load variations, six different types of buildings were retrofitted with high reflectance white coatings or white PVC single-ply membrane at three different geographical sites in California (USA) [43]. It was concluded that the daily peak temperature of the roof surface for all the buildings was lowered by 33–42 K. The tests performed on these single-storey commercial/institutional buildings proved that high reflective roofs are economical for these buildings achieving cooling load savings of 5–40% and the peak demand savings of 5–10%.

4.1.6. Green roofs

A building roof that is either fully or partly covered with a layer of vegetation is called a green roof. It is a layered composite system consisting of a waterproofing membrane, growing medium and the vegetation layer itself. Often, green roofs also include a root barrier layer, drainage layer and, where the climate demands, an irrigation system. There are two types of green roofs: intensive and extensive, the former has a deeper substrate layer and allows to cultivate deep rooting plants such as shrubs and trees; while the latter with thinner substrate layer allows to grow low level planting such as lawn or sedum. Extensive type is more commonly used as it can be retrofitted easily on existing roofs without modifications to the roof structure and also requires minimum maintenance. They have been proven to be fairly successful in cold climates, but needs more research on substrate material in hot and dry climates. The green roofs not only reflect the solar radiation, but also act as an extra thermal insulation layer. They are only meant to improve thermal protection of a building and should not replace the roof insulation layer. The typical additional load associated with an extensive green roof is about 120–150 kg/m^2 [45]. This is in the acceptable range of most buildings. A green roof system incurs higher annual savings when installed on a poorly insulated roof rather than a well-insulated roof.

The moisture content in growing media of the green roof influences its insulating properties. A 100 mm increase in the thickness of dry clay soil led to an increase in resistance by 0.4 m^{2}K/W, whereas for 40% moisture clay soil the increase was only 0.063 m^{2}K/W [46]. The wetter the medium, the poorer the insulating behavior compared to the dry growing media. The equivalent albedo of green roofs is about 0.7–0.85 as against an albedo of 0.1–0.2 for bitumen/tar/gravel roof [34]. Therefore, green roofs reflect solar radiation more efficiently than most conventional roofs. The building energy savings and the retrofit potential of green roofs in UK have been evaluated [62]. The field measurements carried out on low-rise commercial building, in the tropical climatic conditions of Singapore, reported that green roofs helped reduce the thermal reradiation effect experienced with bare roofs [47]. Average heat gain (summer) and heat loss (winter) reductions of 70–90% and 10–30%, respectively, were measured using green roof systems in Toronto, Canada [48]. The performance of green roofs on office buildings in Athens (Greece) is simulated and validated [49]. It is observed through simulations using the DOE-2 computer code that for a turf-type extensive green roof system installed on a non-insulated roof yielded 10.5% annual savings compared to only 0.6% annual savings when installed on an insulated roof [46]. The same conclusions are mathematically validated for Greek climatic conditions [50]. A thermal simulation package ESP-r (Environmental Systems Performance-research) was used to evaluate the performance of a green roof on a multi-storey residential building in Madrid (Spain). The building energy reduction is found to be maximum for the floor immediately below the roof surface and the savings were negligible/none for more than three floors below the roof [51].

Fig. 3 enumerates the various phenomena involved in the energy balance of the solar radiation received by a dry green roof, a wet green roof, and a traditional roof. Although wet soil green roofs disadvantageous as they are poor thermal insulators, they are advantageous in hot and dry climates where evapotranspiration is high. The wet green roofs have almost double the amount of evapotranspiration compared to dry green roofs making them actually remove heat from the building acting as a passive cooler [52].

Table 2
Solar reflectance and infrared emittance properties of typical roof types along with temperature rise [44].

Roof surface type	Solar reflectance	Infrared emittance	Roof surface temperature rise (°C)
Ethylene propylene diene monomer (EPDM)–black	0.06	0.86	46.1
EPDM–white	0.69	0.87	13.9
Thermoplastic polyolefin (TPO)–white	0.83	0.92	6.11
Bitumen–smooth surface	0.06	0.86	46.1
Bitumen–white granules	0.26	0.92	35
Built-up roof (BUR)–dark gravel	0.12	0.90	42.2
BUR–light gravel	0.34	0.90	31.7
Asphalt shingles–generic black granules	0.05	0.91	45.6
Asphalt shingles–generic white granules	0.25	0.91	35.6
Shingles–white elastomeric coating	0.71	0.91	12.2
Shingles–aluminum coating	0.54	0.42	28.3
Steel–new, bare, galvanized	0.61	0.04	30.6
Aluminum	0.61	0.25	26.7
Siliconized polyester–white	0.59	0.85	20.6

4.1.7. Photovoltaic roofs

There have been significant efforts in recent years in integrating photovoltaics (PV) into building envelope. Especially, in countries where land-use is an important constraint, building integrated PV (BIPV) offer an effective solution by the use of building surface area while facilitating energy production and building envelope weather protection. PV roof tiles replace roofing material and are installed directly on to the roof structure. Ceramic tiles or fiber-cement roof slates have crystalline silicon solar cells glued directly on them. Another type of roof-integrated system has a PV element (glass-glass laminate) positioned in a plastic supporting tray anchored to the roof. Due to low cost and physical flexibility there has been growing interest in thin film PV for BIPV applications. Other types of PV roofs include sandwich PV roofing which offers multi-functionality such as electricity generation and thermal insulation [53].

Photovoltaic module based roof systems are still widely installed on sloped or flat roofs. They are either fixed directly on a weather-proof membrane with the help of aluminum framing system with drain trays or retrofit on top of the existing tiles. The generally guaranteed life span of these structures is around 30 years. An average retrofit cost of such system is around 7400 €/kW$_p$ as per the year 2003 prices [53]. The bulk of this cost is attributed to the price of PV modules. The cost of PV has gone down substantially since 2003, which would mean a lower price of these systems.

4.1.8. Thermal roof insulation systems

The thermal insulation for roofs has been of growing importance lately, because on an average as much as 60% of the thermal energy leakage occurs through the roofs. Roof insulation has the potential for saving both cooling and heating loads. The transmittive barrier is a term often used to refer thermal insulation. When accompanied by a reflective surface (viz. an aluminum foil backing), it is referred to as radiant-transmittive barrier (as shown in Fig. 4) as it can also reflect infrared radiation. Polystyrene, fiberglass, rock-wool/mineral-wool are commonly used as roof insulation in the arid climates of Middle-East and Asia. Polystyrene or polyurethane insulation layers have the capability of reducing the load by more than 50% when compared to an identical building roof without insulation [35].

Laboratory experiments have been carried out on different configurations of roofing systems fabricated from five different kinds of insulating materials – polyurethane, polystyrene, polyethylene, sand and rubber along with two different reflector material – aluminum 1100-H14 and galvanized steel sheets [37]. Substantial reduction of heat flux through the roof, as high as up to 88%, is recorded for a combination of flat aluminum 1100 reflector and polyurethane insulator type concrete roof. The general results suggest that aluminum 1100-H14 is a better reflector than galvanized steel. Polyurethane and polystyrene performed better than other insulating materials. The geometry of the reflector seemed to have negligible effect unless there is forced convection [37]. A

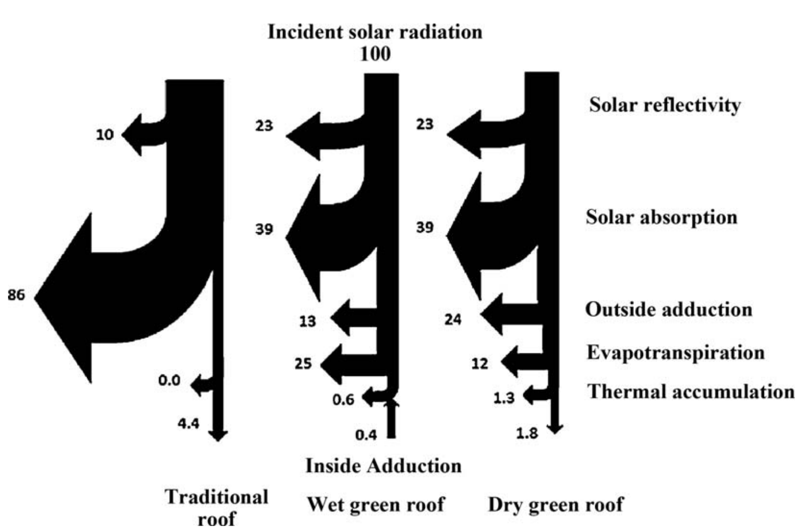


Fig. 3. Comparison of the energy exchanges of the dry or wet green roof with a traditional roof, summer season.
Source: Lazzarin et al. [52].

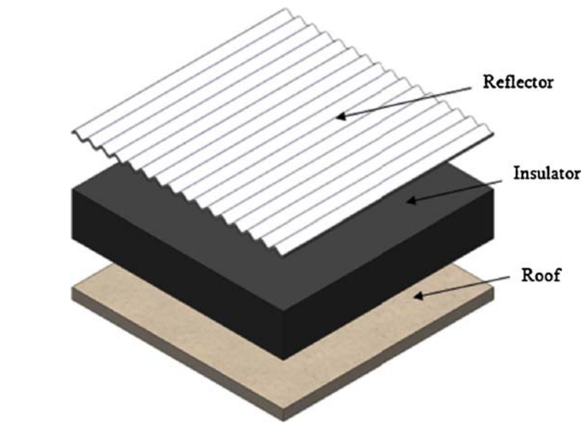


Fig. 4. Radiant-transmittive barrier.
Source: Alvarado et al. [37].

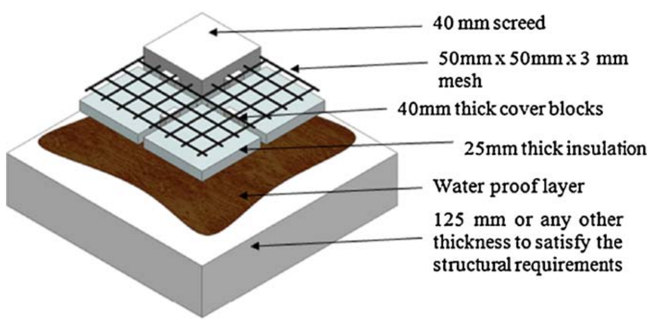


Fig. 5. Roof insulation system.
Source: Halwatura and Jayasinghe [36].

roof insulation system (as shown in Fig. 5) was tested on an occupied building in the tropical climate of Sri Lanka. The insulation used was expanded cellular polyethylene (thermal conductivity – 0.034 $W/m^2 K$). It was observed that an insulation thickness of 25 mm resulted in a soffit temperature reduction of at least 10 °C [36].

4.2. *Evaporative roof cooling*

In evaporative roof cooling, latent heat of evaporation is used to cool a building roof. There are different types of evaporative cooling methods. The techniques that are appropriate for tropical climates are roof ponds and wetted burlap bag covers. A roof pond is a shallow pool of water over a flat roof top with fixed side thermal insulations and a movable top thermal insulation. In summer, the top movable insulation covers the pond during daytime protecting it from solar radiation and exposes it to the environment during the night for nocturnal cooling of the water. In winters, the process happens vice versa, i.e. closed pond during the night and exposed pond during the day. The use of roof pond can lower the room temperature by about 20 °C in summer [35]. Wetted burlap bags are water soaked jute bags that are laid on roof tops to provide evaporative cooling, especially in regions with hot and arid weather. Although the roof temperature can be lowered by as much as 15 °C [35], these methods suffer from non-availability of water. Skytherm or evapo-reflective methods are more preferable in such climatic conditions [37]. A proposed evapo-reflective roof system (as shown in Fig. 6) consists of high thermal capacity rock bed in water over the concrete roof ceiling, a reflective aluminum sheet that encloses on the top and an air gap between the water surface and the aluminum reflector. A simulated comparison suggests that

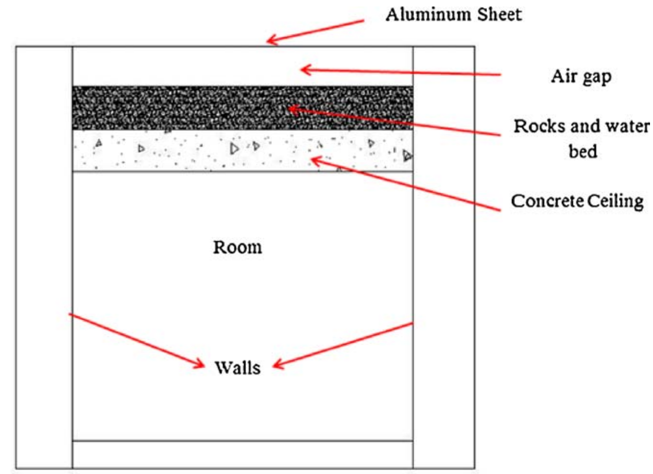


Fig. 6. Evapo-reflective roof cooling system.
Source: Ben Cheikh and Bouchair [54].

this evapo-reflective roof can reduce the indoor temperature by up to 8 °C in comparison to a bare concrete roof [54].

5. Thermal insulation, thermal mass and phase change materials

5.1. *Thermal Insulation*

Thermal insulation is a material or combination of materials, that, when properly applied, retard the rate of heat flow by conduction, convection, and radiation. It retards heat flow into or out of a building due to its high thermal resistance. The proper use of thermal insulation in buildings reduces not only the energy usage but also downsizes the HVAC system during design. A simple and effective way to improve the energy efficiency of a building is by improving the thermal insulation of the envelope. The thickness of insulation in building has increased since the early 1970s, almost doubling in northern Europe [55]. The best performance of thermal insulation is achieved by placing it closest to the surface of heat entry; i.e. in space heating load dominant regions, insulation should be placed close to the inner surface of the building envelope while in cooling load dominant regions it should be closer to the outer surface. Typically, the thickness of the insulation material in a 50 cm thick wall is around 25–30 mm depending on the building codes and regulations across various countries. An economic model to determine the optimum insulation thickness for external walls of a building for various locations in Turkey was developed [56]. Seasonal load savings were estimated using the model.

5.1.1. *Selection of insulation*

The thermal conductivity and thermal inertia are practically the most important factors that affect the selection. The increase in temperature and moisture content of the thermal insulation increases its thermal conductivity, thereby degrading its performance. In fact, studies have shown that water in the form of vapor or liquid has a detrimental effect on the material characteristics of slag-rock wool fibers and fiberglass [57]. Environmental and health impacts are also important factors in selecting an appropriate insulation. The chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) gradually emitted over the life cycle of some foam type insulation materials such as extruded polystyrene (EPS) and polyisocyanurate (PIR) prove detrimental to the environment due to their large ozone depletion and global warming potentials. Insulating foam which contains isocyanates acts as a powerful irritant on eyes and skin. Often times, glass-fiber batt type insulation

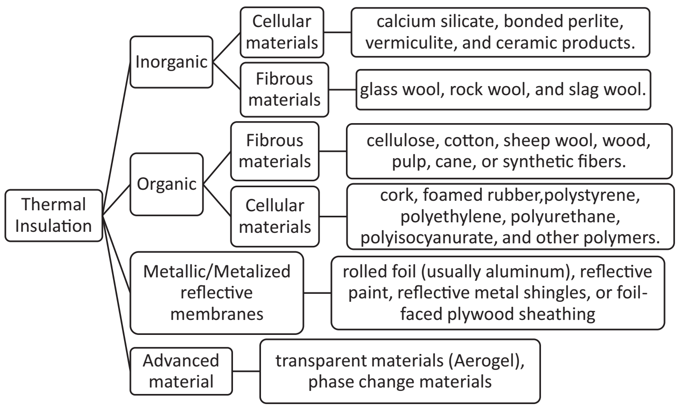


Fig. 7. Different types of thermal insulation.

material is known to cause health related problems, especially respiratory ailments, to the personnel handling it. Flammability is also an important factor in material selection. Rigorous tests check flare spread, fuel contribution, and smoke development rates to classify the flammability of the insulators accordingly. For example, the mixture of flame/glow-retardant chemicals with cellulose (an inherently flammable material) diminishes the fire propagation ability [58]. However, the addition of flame-retardants reduces the thermal resistance of the insulator thus diminishing its performance. Benefit to cost ratio is another important factor that is generally considered in the selection of insulation.

5.1.2. Types of insulation

The thermal insulation is available in different physical forms such as

1. Mineral fiber blankets: batts and rolls (fiberglass and rock wool).
2. Loose fill that can be blown-in (fiberglass, rock wool),
3. Poured-in, or mixed with concrete (cellulose, perlite, vermiculite).
4. Rigid boards (polystyrene, polyurethane, polyisocyanurate, and fiberglass).
5. Foamed or sprayed in-place (polyurethane and polyisocyanurate).
6. Boards or blocks (perlite and vermiculite).
7. Insulated concrete blocks and insulated concrete form.
8. Reflective materials (aluminum foil, ceramic coatings).

The types of insulation can be classified into 4 categories and respective subcategories depending on their material type as shown in Fig. 7 [55,59].

5.1.3. Vacuum insulation panels

Vacuum insulation panels are high performance thermal insulators made up of evacuated foil-encapsulated porous material. The selection of core material that can maintain vacuum is a challenge. Fumed silica (SiO_x) is one such material that suits the requirements of core material. Pressed boards made out of fumed silica has a low conductivity (close to 0.003 W/m K at 50 mbar) and has a conductivity of 0.020 W/m K at ambient pressure in dry conditions, half the thermal conductivity of traditional insulation materials [60].

5.1.4. Structurally insulated panels (SIPs)

Structurally insulated panels (SIPs) are pre-fabricated composite building elements used as walls, roofs, ceilings and floors. SIPs consist of insulation sandwiched between two structural boards. The commonly used insulation materials in SIPs are expanded polystyrene foam and polyurethane foam. In some cases, straw bales are also used as sustainable insulation material. The SIPs are manufactured in factories and shipped to job site allowing quicker installation, a major advantage of SIPs.

5.2. Thermal mass

Thermal mass refers to the high heat capacity materials that can absorb heat, store it and release it later. They include building components such as walls, partitions, ceilings, floors and furniture of a building that can store thermal energy. It helps in the regulation of indoor temperature by absorbing and progressively releasing the heat gained through both external and internal means. This leads to delaying/reducing the peak indoor loads and decreasing the mean radiant temperature [61,62]. For thermal storage to be effective, the diurnal ambient temperature variation should exceed 10 K. The thermal mass optimization is effected by the thermo-physical properties of the building material, building orientation, thermal insulation, ventilation, auxiliary cooling systems and occupancy patterns. This passive building energy efficiency technique is more effective to buildings such as offices that are unoccupied during the night when the thermal mass can be cooled with nighttime ventilation [62]. The effects of thermal mass and night ventilation on building cooling load are mathematically modeled [63]. In a case study on a 27,000 ft^2 commercial building in northern New York, energy savings of 18–20% (12.2–16.0 $kBtu/ft^2$) were achieved through addition of thermal mass. Reduction in both peak heating and cooling loads led to the downsizing of the HVAC system, offsetting the capital investment spent on thermal mass addition [64]. In a study, six different envelope configurations were compared through computational simulations. It was concluded that the position and distribution of thermal mass in the building envelope does not influence energy savings for high rise buildings in cold climates [65].

5.3. Phase change materials (PCM)

Phase change materials store and release heat to reduce the cooling and heating loads of a building. They basically function as a thermal mass and accomplish that by liquefying as they absorb heat, preventing the heat from reaching the conditioned space and releasing the heat when the outside temperature decreases (typically at night). A recent experimental work carried out by Arizona Public Service (APS) in collaboration with Phase Change Energy Solutions (PCES) Inc. with a new class of organic-based PCM (BioPCM) showed maximum energy savings of about 30%, a maximum peak load shift of about 60 min, and a maximum cost savings of about 30% over conventional non-PCM base-case. Also, unlike other organic based PCMs which are highly flammable, the BioPCM used in this case is less flammable and safer to use [66]. Feldman et al. [67] used differential calorimetry technique to determine the transition temperatures and latent heats of transition of fatty acids (capric, lauric, palmitic and stearic) and their binary mixtures, which are all attractive candidates for latent heat thermal storage. The PCM absorption capacity of 10 different building envelope materials was presented [68]. The PCM used in this case was a mixture of 50% butyl stearate and 48% palmitic acid.

6. Infiltration and airtightness

The movement of air into the conditioned space of a building through cracks, leaks, or other building envelope openings is referred as infiltration, and out of the building is called exfiltration. Infiltration affects the air conditioning load, temperature and moisture levels of indoor air in buildings. Also, when infiltrated air encounters colder regions of the building envelope, water vapor condenses which is not desirable due to various reasons such as

promotion of mold and mildew growth, etc. [69]. Caulking/sealing of air leakage cracks and penetrations can improve the energy efficiency of a building by minimizing infiltration.

Unlike infiltration which depends on the pressures across the building envelope, airtightness of a building is independent of these naturally induced pressures. That is why it is an important parameter in building stock characterization, modeling assumptions or construction quality control. The measure of both infiltration and airtightness of a building are important from energy and indoor air quality (pollutant and moisture transports) standpoints.

6.1. Factors affecting infiltration

Infiltration is driven by a pressure difference across the building envelope caused due to temperature difference between indoor and outdoor air (stack effect), wind movement and operation of mechanical ventilation equipment and vented combustion devices. The rate of infiltration is affected by climatic factors, building surroundings, building age and building construction characteristics. During indoor heating, air tends to infiltrate the building through the leaks low in the building envelope and exfiltrate from the leaks high in the building envelope. The airflow patterns are reversed during indoor cooling. Ignoring the internal airflow resistance, the stack pressure difference is around 0.02 Pa per meter of building height and degree Celsius of indoor–outdoor temperature difference. Generally, lower wind speeds (2.5 m/s or less) generate an exterior wind pressure of 1 or 2 Pa; whereas higher wind speeds (10 m/s or more) can generate pressure of 25 Pa or more [70]. The operation of mechanical equipment, ventilation systems, local exhaust fans, and vented combustion appliances causes a net flow of air into the building or out of the building, thereby causing a respective raise or fall of the interior building pressure.

6.2. Mathematical formulation of infiltration

Generally, the power laws of the form $\Delta P = \alpha Q^{\beta}$ establish a relation between pressure drop (ΔP) and volume flow rate (Q) in flow through cracks. Other laws, such as the square law (where $\Delta P = \alpha Q^2$) are also applicable to some types of leakage or crack geometries and pressure differences where fully developed turbulent flow is encountered. Here ‘α’ is a constant dependent on effective leakage area of the crack. In a different study, experiments on pressurization testing of windows resulted in quadratic law of the form: $\Delta P = \mathrm{AQ} + \mathrm{BQ}^2$. The coefficients $A = 12\,\mu z/Ld^3$ and $B = \rho C/2d^2L^2$ in this equation are independent of the flow rate. This law described experimental data better than the power law for window pressurization test [71]. Although the quadratic form addresses a wide range of laminar and turbulent flow rates, the equation inherently assumes a fully developed flow through leaks and cracks. However, this fully developed flow assumption is not valid as flow through the cracks is mostly developing, and also the transient pressure difference across the building envelope in real situation worsens the likelihood of a fully developed flow. A power law of the flow equation has been proven to better represent the infiltration across a building envelope [72]. ASHRAE crack method [73] and empirical equations derived from air tightness test results by Persily [74] for air leakages and infiltration appear to endorse the use of the power law form.

6.3. Pollutant infiltration

Buildings are ventilated by three means, namely: mechanical ventilation (induced by fans, blowers etc.), natural ventilation through fenestration (due to wind and buoyancy force) and infiltration through cracks and leaks. In mechanically ventilated buildings, the effectiveness of the filters influences the penetration of ambient particles. While in naturally ventilated buildings, particle penetration approaches unity because of the air exchange openings are large. In infiltration governed air change, particle penetration depends on geometry of air leakage path, pressure difference that drives the flow and particle transport properties. Although filters and other cleaning equipment minimize the pollutant levels in buildings, different particles and reactive gases enter through infiltration. Diesel soot, constituents of photochemical smog, industrial particulate emissions, aerosols, airborne pollen, spores and microbial volatile organic compounds from molds in building envelope are some examples of such urban pollutants [75]. Higher particle concentrations in the indoor air lead to adverse effects on human health. These concentrations depend primarily on the degree of penetration of these particles through the building envelope [76].

Rectangular/regular geometry surrogates of the real infiltration paths were developed using seven commonly-used building materials: aluminum, brick, concrete, plywood, redwood lumber, pine lumber and strand board. The crack heights were selected to be 0.25 and 1 mm to closely represent those in a real building. The length of the crack in direction of airflow was 4.3 and 9.9 mm for aluminum cracks and 4.5 mm for other materials. Also, the pressure difference across the crack was maintained similar to that of a normal building envelope 4 or 10 Pa. Particle penetration is almost 100% for particles of diameter 0.02–7 μm when the crack height is $\geq$1 mm. It is almost 95% for particles of diameter 0.1–1 μm when the crack height is $\geq$0.25 mm, assuming the pressure difference is at least 4 Pa. It was experimentally proven that the surface roughness and irregular crack geometries has a bearing on the particle penetration [76].

6.4. Infiltration and air tightness case studies

Persily et al. [69], collected air leakage data from over 70,000 U.S. homes. The average air leakage of these homes was about 20 air changes per hour at 50 Pa pressure difference, although conventional new houses constructed since 1993 seem to have an average value of 10 air changes per hour. Energy efficiency construction programs have reportedly reduced this value to 5 air changes per hour (ACH) for new houses. Also, against the popular belief in the U.S. that commercial and institutional buildings are relatively airtight, it was proven that they are more conducive to increased leakage than conventional new houses in the U.S. The U.S. commercial and institutional building data also proves that taller commercial/institutional buildings are tighter than shorter ones and, so did the buildings in colder climates than in warmer climates. It appears that the type of construction practices in taller buildings lend themselves more to airtight envelopes. The general residential building data obtained in USA suggests that 2 air changes per hour at 50 Pa could be considered a very tight house. A value of 5 air changes per hour could be considered moderately tight, while 10 air changes per hour could be considered typical and 20 air changes per hour can be classified leaky [74]. The data from 139 commercial and institutional buildings analyzed by Persily [74] have shown that taller buildings are more airtight than shorter buildings. The more careful design and construction to meet the structural demands of tall buildings may have yielded to their better air-tightness.

Experimental studies have been conducted to measure the infiltration on 20 residential buildings in Greece, a representative of Mediterranean/southern European type of climate [70]. These naturally ventilated building envelopes (with more than one exposed façade) are classified into three categories based on their air tightness and infiltration under natural conditions. This classification complies with the standard EN ISO 13790 that defines three categories of building air tightness levels: high, medium and low. The air tightness measured from a blower door test (at 50 Pa pressure

difference) should be less than 4 ACH or infiltration rate measured from tracer gas decay should be less than 0.5 ACH to be classified as 'high' level of envelope tightness. Similarly, a 'low' level of envelope tightness indicates 10 ACH (or higher) or infiltration rate of 1.5 ACH (or higher). A 'medium' level of envelope tightness designates 4–10 ACH or infiltration rate of 0.8 ACH.

7. Building simulation software/programs

The building energy modeling codes can be used to estimate the energy performance of a building envelope, energy used in the building, HVAC sizing, estimate lighting requirements, economic feasibility estimates for building energy efficiency components, comparison of a building performance with a code standard building, etc. These codes can be used by building designers as guiding tools to develop an optimal energy efficient building. The modeling tools can also be used to predict a cost effective energy efficiency retrofit to an existing building. Several building energy modeling codes have been developed by different groups over the years. The accuracy of the building energy simulations heavily depends on the user input data such as building geometry and orientation, construction details, geographic location, mechanical equipment, type of building (residential or commercial), etc.

Crawley et al. [77] performed an up-to-date comparison of the features and capabilities of 20 major building energy simulation codes. The codes include BLAST, BSim,DeST, DOE-2.1E, ECOTECT, Ener-Win, Energy Express, Energy-10, EnergyPlus, eQUEST, ESP-r, IDA ICE, IES/VES, HAP, HEED, PowerDomus, SUNREL, Tas, TRACE and TRNSYS. The capabilities of these codes to model building envelope, daylighting and infiltration in buildings are also discussed. Antinucci et al. [62] identified 128 models with building energy simulation capabilities. Of those programs 54 can evaluate the variation in indoor air temperature, 45 can also consider the impact of thermal mass and shading, 48 tools include daylighting subroutines, whereas only 23 programs can simulate natural ventilation strategies. Most of these programs are compiled for architects and engineers, although some of them can be useful to technicians, builders and researchers. The majority of these programs can be used for simulation of residential and small-size commercial buildings, while only 47 of them have some capability of simulating large-size commercial buildings.

Apart from above mentioned software, there are certain specific computer programs that deal with simulation of the performance characteristics of certain envelope components. Programs such as Window, VISION4, FRAME4, FRAMEPlus, FENSIZE, Frame Simulator, RESFEN, SPACER etc. are used to simulate thermal performance characteristics of fenestration. GLASTRUCT and FENSTRUCT are used to simulate the structural performance of fenestration. Fenspec and Catalogue are multi-vendor databases for windows/fenestration products that can be searched for options that meet a designer's physical and performance criteria.

AWNSHADE, LESO-Shade, ParaSol, ShadowFX, Solar-2, Solarch, Sun Chart, SunCast, Sundi and SunPath are some shading/solar design tools that assist in analyzing the qualitative aspect of solar design (such as building appearance, lighting, glare) rather than quantitative energy issues.

CONTAM is a multi-zone indoor air quality and air flow analysis program that helps determine infiltration, exfiltration, room-to-room air flows, induced pressure differences due to indoor and outdoor temperature difference, wind movement and mechanical means, contaminant concentrations, occupant exposure patterns, etc. [78].

8. Building envelope diagnostics

Building envelopes, like any other components of the building, should receive regular and thorough inspection. The inspection techniques may vary from simple visual inspection through binoculars to sophisticated IR thermography.

8.1. Infrared thermography

The thermal infrared (IR) imaging is a handy diagnostic tool used for detecting building envelope defects. IR inspections are useful in detecting building energy problems such as heat losses, missing or damaged thermal insulation in walls and roofs, thermal bridges, air leakage and moisture sources. It is non-destructive and non-contact in operation and can be used to easily inspect remote regions of the envelope. The accuracy of the leakage measurement is dependent on various factors such as emissivity of the measured surface, air particles, ambient temperature, wind speed and distance from the target [79]. Most non-metallic surfaces such as paint, wood and plastics have high emissivity values greater than 0.8. For clean, well-polished, shiny metal surfaces, the emissivity is typically between 0.05 and 0.2, though oxide layer impurities can increase the emissivity values. Generally, a high emissivity surface (such as paper stickers, water soluble black paint, electrician's tape) can be affixed on a low emissivity surface (less than 0.5) while executing the measurement. A vivid description of emissivity measurement technique and the details of error corrections are described [80]. Atmospheric particles between the source and the lens of the IR camera cause transmission attenuation of IR radiation and the ambient air temperature affects the temperature of the IR radiation sensing equipment. IR equipment, usually have an internal compensation system that will correct these variations. Wind speed of 5 m/s or higher can influence the measurements due to convective heat losses. The distance of the target and the angle of vision influence the resolution and quality of the IR image. Farther distances and higher oblique angles of vision can lead to poor resolution and quality of the picture [79].

8.2. Fenestration diagnostics

Portable spectrometer or solar transmission meter is used to measure the emissivity of fenestration glazing. A portable handheld spectrometer is a surface-contact tool that uses an infrared emitter and detector to estimate the aggregate normal reflectance of a multi-pane glazing assembly. It is more convenient to use than solar transmission meter. The use of solar transmission meter on a fixed (non-opening) fenestration is impractical because it requires measuring irradiance with and without the glazing in the irradiance path. Neither of these devices can differentiate a low-e pane from a non-low-e pane nor can they determine the thickness of inter-pane gap. A handheld laser thickness gauge is used for such measurements [81].

8.3. Infiltration and airtightness diagnostics

Tracer gas measurements are used to calculate infiltration rates in buildings. The tracer gas released in the buildings is usually nitrous oxide (N_2O) whose concentration decays as it mixes with the indoor air. The N_2O concentration is traced to determine the infiltration rate in air changes per hour (ACH or h^{-1}). ASTM standard E741 details various tracer gas methods applicable to single zone buildings.

The airtightness of a building is measured by blower door test or fan pressurization test. The blower door test is generally used for low rise residential buildings and is carried out at various induced pressures (generally at 50 Pa). ASTM standard E1827 describes the blower door test that employs an orifice approach to measure air flow rate. In commercial buildings, fan pressurization test, which is analogous to blower door test, is conducted to determine airtightness. The fan pressurization test method is

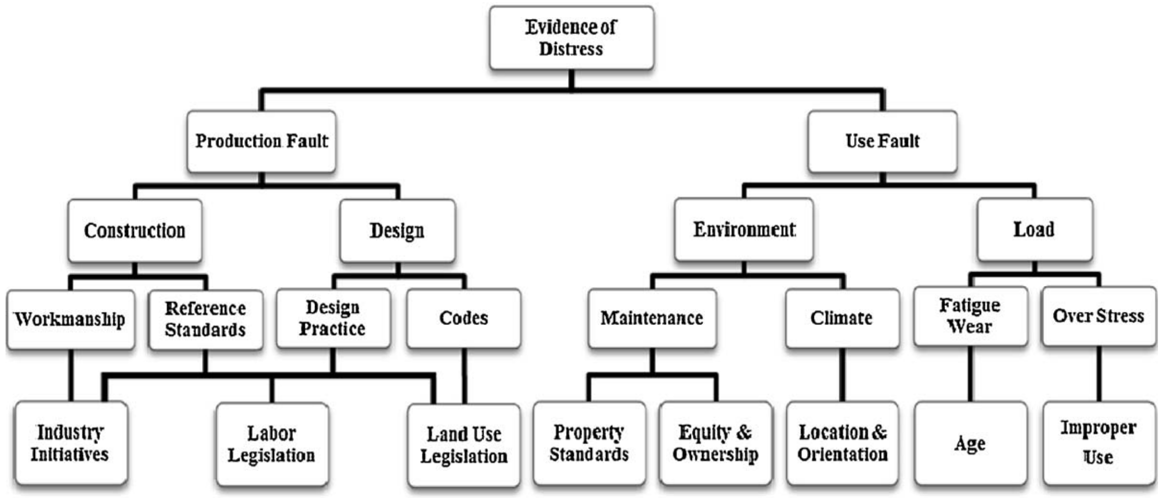


Fig. 8. Fault tree tool.

Source: Genge [83].

described comprehensively by ASTM standard E779. EN ISO 13829 also elucidates the fan pressurization test procedure in detail [82]. Elevated pressure differences in the range of 10 to 75 Pa are created between the interior and exterior of a building using a fan or a blower to override any weather factors influencing the pressure difference. The airtightness is calculated from the airflow rates required to maintain these induced pressure differences.

8.4. Envelope moisture diagnostics

The areas of moisture anomalies in building envelopes are identified using in situ moisture measurement procedures. Surface scanning dielectric meters and penetrating conductance meters are used to quantify the presence of moisture in non-conductive porous building material. Since both these devices are electrical based, they are susceptible to presence of static electricity and conductive materials. Of these, surface scanning techniques are advantageous because they do not damage the envelope surface and can be used on large surfaces. On the other hand, the penetrating conductance technique damages the envelope surface due to insertion of probes. The penetration method is often used after the surface scanning method to get accurate measurements.

9. Building envelope maintenance

Since building envelopes separate the indoor and outdoor environments, they are subjected to environmental effects of temperature, humidity, air movement, rain, snow, solar radiation and various other natural factors. It is important to carry out building envelope maintenance to ensure quality living/working/industrial environments and to avoid premature failure of the building structure. There are two types of building envelope maintenance—'Routine' maintenance involves regularly scheduled inspections, repairs or replacement of building envelope components and 'Response' maintenance involves emergency or immediate maintenance where failed components are repaired or replaced. Generally, building envelope repair and replacement costs contribute 20–30% of the overall building repair and maintenance life cycle costs [83]. The building envelope repair calls are the most frequent of all building repair calls, especially in high-rise structures and extreme climates [84]. Investment on annual maintenance audits and professional review of the general performance of building envelope components can prevent premature and costly failures.

One of the commonly encountered building envelope maintenance issues is water run-off damage. Whenever water runs down over building envelope components, it can leave behind contaminants that react with or adhere to the surface of the exposed envelope components, thus causing a temporary or permanent damage to the building envelope [84]. Building envelopes also need to be designed and protected from two wind storm effects: windborne debris and fluctuating pressures. This is an important consideration in hurricane/tropical cyclone/typhoon prone areas. A review of the wind storm effects on building envelopes conclude that the fenestration of high rise buildings are most affected due to the hurricane winds [85]. Some of the building codes and standards concerning the windborne debris and fluctuating pressures impact on the building envelope are also discussed in this review.

Commonly, considerable effort may be spent on examining, categorizing and documenting the symptoms of fault (distress) rather than the fault itself. For instance water leaks, efflorescence, spalled brick, etc., are often classified as fault when they actually are the symptoms of fault (distress). The fault tree tool that is useful in inspecting the building envelope performance is shown in Fig. 8. This tool helps the investigator identify the fault(s) causing the distress rather than the distress (symptom of fault). The fault tree is divided into two main divisions—the left branch is concerned with faults encountered during the creation of a building while the right branch is concerned with faults encountered during the operation of a building. Any identified building envelope distress may be related to one or more faults shown in the fault tree. Once those faults are identified, the necessary repair or replacement action can be initiated depending on the operational, financial and technical constraints to minimize or eradicate the distress [83].

10. Conclusion

This article reviewed various building envelope components from an energy efficiency and savings perspective. Improvements to building envelope elements are generally referred as passive energy efficiency strategies. Passive energy efficiency strategies are highly sensitive to meteorological factors and, therefore, require a broader understanding of the climatic factors by a designer. For example, application of thermal mass as an energy saving method is more effective in places where the atmospheric air temperature differences between the days and nights are high. Building energy modeling computer codes play an important role in choosing the best energy efficiency options for a given location. In order to

ensure proper operation of the designed envelope, building envelope commissioning is essential. Periodic energy auditing of the building envelopes and maintenance are important to achieve the best energy performance and extended life for a building envelope.

Currently, while some of these advances in envelope component technologies are easy and cost effective to adopt, others still remain in the research and development phase for future applicability. Several studies have been performed to find the economic feasibility of various building energy efficiency strategies [86–88]. Cost-benefit analysis of some of these energy efficiency strategies for a cooling dominated desert climate is presented by Sadineni et al. [89]. Energy efficiency approaches sometimes might not require additional capital investment. For example, a holistic energy efficient building design approach can reduce the size of mechanical systems compensating the additional cost of energy efficiency features. Government incentives and rebates in many parts of the world are promoting the market penetration and social awareness of these technologies.

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